Naval Research Laboratory
Washington, DC 20375-5000

NRL Memorandum Report 6541

Frequency Shifts Induced in Laser Pulses by Plasma Density Variations

E. ESAREY, A. TING AND P. SPRANGLE

Beam Physics Branch
Plasma Physics Division

October 25, 1989

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 6541	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory 6b. OFFICE SYMBOL (If applicable) Code 4790	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION DOE 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20545	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. | PROJECT NO DOE#AI05 83ER40117 | TASK NO. | WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Frequency Shifts Induced in Laser Pulses by Plasma Density Variations

12. PERSONAL AUTHOR(S)
Esarey, E., Ting, A. and Sprangle, P.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Interim	FROM ______ TO ______	1989 October 25	20

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Laser-plasma interactions, Plasma variations, Frequency shifts

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

An analytical theory is developed which describes how a radiation pulse becomes modified as it propagates through a plasma with arbitrary temporal and spatial density variations. Expressions are derived for the shifts induced in both the frequency and the wavenumber of the radiation pulse. It is shown that temporal variations in the plasma density result in frequency shifts of the radiation. The possibility of upshifting the frequency of the laser pulse using plasma waves is analyzed, and it is found that maximum shifts occur when the phase velocity of the plasma wave is equal to the group velocity of the laser pulse.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL E. Esarey	22b. TELEPHONE (Include Area Code) (202) 404-7720 22c. OFFICE SYMBOL Code 4790

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603

FREQUENCY SHIFTS INDUCED IN LASER PULSES BY PLASMA DENSITY VARIATIONS

The propagation of electromagnetic radiation through plasmas is a problem of general interest with a wide variety of applications ranging from communications[1] to laser driven particle accelerators.[2,3] For example, the results of plasma simulation studies have recently been reported[4,5] which suggest two possible methods by which the frequency of an electromagnetic wave may be upshifted. In the first method, the plasma density through which the EM wave is propagating is suddenly increased in time,[4] while the second method utilizes the interaction of a plasma wave (having a phase velocity near the speed of light)[2,3,6,7] with a short EM pulse.[5] Phenomena such as these, which result from variations in the plasma density, may offer a way of tuning the radiation from a laser or, alternatively, they may describe the distortion of radio signals in the ionosphere.

In the following, a general analytic theory is developed from first principles which describes how a EM radiation pulse is affected by variations in the plasma density. Specifically, the 1D wave equation is used to derive expressions for the shifts induced in the frequency and in the wavenumber by arbitrary plasma density variations (both in space and in time). In particular, for variations in the plasma density as a function of time, it is shown that the wavenumber of the EM wave remains constant while shifts are induced in the frequency. (This is to be contrasted to the case of spatial plasma density variations, for which the frequency remains constant and the wavenumber shifts.) For the case of a short radiation pulse interacting with a plasma wave with finite phase velocity, it is shown that shifts are induced in both the wavenumber and in the frequency. Maximum frequency shifts may be obtained when the phase velocity of the plasma wave is equal to the group velocity of the radiation pulse evaluated at the ambient plasma density. Furthermore, it is shown that for small frequency shifts, the amplitude of the vector potential maintains its initial profile while propagating forward at the ambient group velocity.

The 1D wave equation for the normalized vector potential $a = eA/(mc^2)$ of the radiation field is given by

$$\left(\frac{\partial^2}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) a(z,t) = k_p^2(z,t)a(z,t), \tag{1}$$

where $k_p^2 \equiv k_{p0}^2 n(z,t)/(\gamma(z,t)n_0)$. Here $\gamma(z,t)$ is the relativistic factor associated with the motion of the plasma electrons, $n(z,t)$ is the plasma electron density and $k_{p0}^2 = \omega_{p0}^2/c^2$, where ω_{p0} is the electron plasma frequency in the ambient density n_0. In deriving the above equation, conservation of canonical momentum was used, $p_\perp = eA_\perp/c$, which gives a transverse plasma current (in the fluid limit) of $J_\perp \equiv -enp_\perp/(m\gamma)$. Throughout the

Manuscript approved September 8, 1989.

following it will be assumed that $a^2 << 1$ such that $k_p^2(z,t)$ is independent of $a(z,t)$, i.e., the effects of the radiation field on the plasma wave will be ignored.

To solve the above wave equation, it is helpful to write $a(z,t) = b(z,t)\exp(ik_0 z - i\omega_0 t)$, where $b(z,t)$ is the radiation envelope and where ω_0 and k_0 are the frequency and wavenumber of the radiation in the ambient plasma (in the absence of a plasma wave) which satisfy the dispersion relation $\omega_0^2 = c^2 k_0^2 + c^2 k_{p0}^2$. Furthermore, it is convenient to introduce a change of variables $\zeta = z - v_g t$ and $\tau = t$, where $v_g = c^2 k_0/\omega_0$ is the group velocity of the radiation in the ambient plasma. The wave equation is then given by

$$\left(2i\frac{\omega_0}{c^2}\frac{\partial}{\partial\tau} + 2\frac{v_g}{c^2}\frac{\partial^2}{\partial\zeta\partial\tau} + \frac{1}{\gamma_g^2}\frac{\partial^2}{\partial\zeta^2} - \frac{1}{c^2}\frac{\partial^2}{\partial\tau^2}\right) b = \delta k_p^2(\zeta,\tau) b(\zeta,\tau), \tag{2}$$

where $\delta k_p^2 \equiv k_p^2 - k_{p0}^2$ and $1/\gamma_g^2 = 1 - v_g^2/c^2$.

It will now be assumed that the radiation envelope $b(\zeta,\tau)$ is slowly varying compared to the radiation frequency ω_0, that is $|\partial b/\partial\tau| << |\omega_0 b|$ and $|\partial b/\partial\zeta| << |\omega_0 b/c|$. Assuming this, the second order derivatives in Eq. (2) may be neglected. Equation (2) may then be solved giving

$$b(\zeta,\tau) = b_0(\zeta)\exp\left[-\frac{ic^2}{2\omega_0}\int_0^\tau d\tau' \delta k_p^2(\zeta,\tau')\right]. \tag{3}$$

The condition $|\partial b/\partial\tau| << |\omega_0 b|$ implies $|c^2\delta k_p^2/(2\omega_0^2)| << 1$. For a plasma density perturbation δn, this condition implies $|\omega_{p0}^2\delta n/(2\omega_0^2 n_0)| << 1$. The condition $|\partial b/\partial\zeta| << |\omega_0 b/c|$ implies $|\int_0^\tau d\tau'(\partial\delta k_p^2/\partial\zeta)c^3/(2\omega_0^2)| << 1$ as well as $|(db_0/d\zeta)c/(b_0\omega_0)| << 1$. The first of these inequalities generally implies that the wavenumber shift must be small compared to ω_0/c, while the second inequality indicates that the initial envelope $b_0(\zeta)$ must be slowly varying compared to ω_0/c.

The total phase $\Phi(\zeta,\tau)$ of the radiation field may be identified by writing $a(\zeta,\tau) = |a(\zeta,\tau)|\exp i\Phi(\zeta,\tau)$. It is then possible to examine the evolution of the frequency as well as the wavenumber of the radiation through the definitions $\omega(\zeta,\tau) \equiv -\partial\Phi/\partial t = -(\partial/\partial\tau - v_g\partial/\partial\zeta)\Phi$ and $k(\zeta,\tau) \equiv \partial\Phi/\partial z = \partial\Phi/\partial\zeta$. Using the above solution for $b(\zeta,\tau)$ gives

$$\omega(\zeta,\tau) = \omega_0 + \frac{c^2}{2\omega_0}\delta k_p^2(\zeta,\tau) - \frac{v_g c^2}{2\omega_0}\int_0^\tau d\tau'\frac{\partial}{\partial\zeta}\delta k_p^2(\zeta,\tau'), \tag{4}$$

$$k(\zeta,\tau) = k_0 - \frac{c^2}{2\omega_0}\int_0^\tau d\tau'\frac{\partial}{\partial\zeta}\delta k_p^2(\zeta,\tau'). \tag{5}$$

The above equations are valid for arbitrary variations $\delta k_p^2(\zeta,\tau)$. (Recall, $k_p^2 = k_{p0}^2 n/(n_0\gamma)$ and the effects of γ become important for nonlinear relativistic plasma waves.[7]) Provided

$b(\zeta,\tau)$ remains slowly varying compared to ω_0, the amplitude of the normalized vector potential $|a|$ does not change. That is, Eq. (3) indicates that $|a| = |b_0(\zeta)|$ and, hence, the initial envelope of the vector potential is simply convected forward at the group velocity v_g.

To illustrate the above theory, consider a plasma density variation which is a function only of space. For example, consider a radiation pulse entering a plasma ($\omega_p^2/\omega_0^2 << 1$) from vacuum with a plasma density profile $\delta k_p^2 = \delta k_p^2(z)$ for $z > 0$ and equal to zero for $z < 0$. Assume that at $t = 0$, the radiation pulse extends from $-L < z < 0$, where $\omega_0 L/c >> 1$. Equations (3)-(5) indicate, that as the pulse propagates, the frequency and wavenumber evolve according to $\omega(z,t) = \omega_0$ and $k(z,t) = k_0 - c^2\delta k_p^2(z)/(2v_g\omega_0)$. This is in agreement with the well–known result[1] that as radiation propagates into a plasma with spatial density variations, the frequency remains constant whereas the wavenumber changes such that the dispersion relation $\omega^2 = c^2(k^2 + k_p^2)$ remains satisfied.

On the other hand, consider a plasma density variation which is a function only of time. For example, consider a radiation pulse (of length $L >> c/\omega_0$) propagating through a long, uniform plasma column (where $\omega_p^2/\omega_0^2 << 1$) in which the density is temporally changing, $\delta k_p^2 = \delta k_p^2(t)$. Equations (3)-(5) indicate, that as the pulse propagates, the frequency and wavenumber evolve according to $\omega(z,t) = \omega_0 + c^2\delta k_p^2(z)/(2\omega_0)$ and $k(z,t) = k_0$. This is in agreement with the simulations of Ref. 4 which indicate that as radiation propagates through a plasma with temporal density variations, the wavenumber remains constant whereas the frequency changes such that the dispersion relation $\omega^2 = c^2(k^2 + k_p^2)$ remains satisfied.

Consider a plasma density variation which is a function both of time and of space. For example, consider the case in which a plasma wave (with phase velocity near c)[2,3,6,7] is used to upshift the frequency of a laser pulse, as suggested by the simulations of Ref. 5. Assuming a plasma wave with a phase velocity v_p such that the plasma wave quantities are functions of only $z - v_p t$ implies $\delta k_p^2(\zeta,\tau) = \delta k_p^2(\zeta - \Delta v\tau)$, where $\delta k_p^2(\zeta - \Delta v\tau)$ has the form of a periodic oscillation and $\Delta v = v_p - v_g$. Defining the shift in frequency and in wavenumber as $\Delta\omega = \omega(\zeta,\tau) - \omega(\zeta,0)$ and $\Delta k = k(\zeta,\tau) - k(\zeta,0)$ gives

$$\Delta\omega = \frac{c^2 v_p}{2\omega_0\Delta v}\left[\delta k_p^2(\zeta - \Delta v\tau) - \delta k_p^2(\zeta)\right], \qquad (6)$$

$$\Delta k = \frac{c^2}{2\omega_0\Delta v}\left[\delta k_p^2(\zeta - \Delta v\tau) - \delta k_p^2(\zeta)\right]. \qquad (7)$$

The above equations indicate that the frequency shift will be maximum for the case

$v_p = v_g$. For this case $\Delta\omega = -(v_g\tau c^2/2\omega_0)d\delta k_p^2/d\zeta$ and $\Delta k = -(c^2\tau/2\omega_0)d\delta k_p^2/d\zeta$. Hence, $\Delta\omega$ is a linear function of $v_g\tau$, the distance that the pulse has propagated through the plasma. In such a way $|\Delta\omega|$ will increase until it becomes sufficiently large so that the approximation that $b(\zeta,\tau)$ is slowly varying is no longer valid. For $b(\zeta,\tau)$ to be slowly varying requires $|c\Delta\omega/(v_g\omega_0)|^2 << 1$. Consider a plasma wave with $v_p = v_g$ such that $\delta k_p^2(\zeta) = k_{p0}^2\delta n(\zeta)/n_0$, where $\delta n(\zeta)$ is the plasma wave density perturbation. For $\delta n(\zeta) = \delta n_0 \sin k_{p0}\zeta$, then

$$\frac{\Delta\omega}{\omega_0} = -\pi\frac{\omega_{p0}^2}{\omega_0^2}\frac{\delta n_0}{n_0}\frac{v_g\tau}{\lambda_{p0}}\cos k_{p0}\zeta. \tag{8}$$

Hence, a positive frequency shift $\Delta\omega > 0$ requires the laser pulse to be positioned properly in the phase of the plasma wave such that $d\delta n/d\zeta < 0$. This is illustrated in Fig. 1. A convenient method for producing such a plasma wave may be the laser wakefield accelerator,[3] in which a driving laser pulse of frequency ω_0 is used to generate a plasma wave with $v_p = v_g$.

For the case $v_p \neq v_g$, $|\Delta\omega|$ is no longer a linearly increasing function of $c\tau$. In fact, Eq. (6) indicates that $\Delta\omega$ will oscillate as a function of $c\tau$. Consider a plasma wave of the form $\delta k_p^2(\zeta,\tau) = k_{p0}^2|\delta n/n_0|\cos k_{p0}(\zeta - \Delta v\tau)$. Assuming the laser pulse (with a pulse length $L << \lambda_{p0} = 2\pi/k_{p0}$) is initially centered about $\zeta_0 = 0$, Eq. (6) indicates that the maximum frequency shift is given by $|\Delta\omega_m| = |\omega_{p0}^2 v_p\delta n_0/(\omega_0 n_0\Delta v)|$ and occurs when $c\tau = |\lambda_{p0}/(2\Delta v)|$. Furthermore, notice that $\Delta\omega_m$ may either be positive or negative, depending on the sign of Δv (for the present example, $\Delta\omega_m > 0$ for $v_p < v_g$). Again, the assumption that $b(\zeta,\tau)$ is slowly varying implies $|c\Delta\omega_m/(2v_p\omega_0)|^2 << 1$.

Physically, the frequency shifts induced in a radiation pulse by a plasma wave may be understood as follows. A plasma wave gives rise to variations in the plasma parameter $k_p^2(\zeta,\tau)$. These variations lead to variations in the "local" phase velocity of the laser pulse. Heuristically, the "local" dispersion relation for the radiation field is given by $\omega^2(\zeta,\tau) = c^2k^2(\zeta,\tau) + c^2k_p^2(\zeta,\tau)$. For small $c\tau$, this gives $v_p^2(\zeta)/c^2 = 1 + k_{p0}^2 n(\zeta)/(k_0^2 n_0)$. For example, the local phase velocity near the front of the laser pulse ($\zeta = \zeta_0$) will be less than the local phase velocity near the back of the pulse ($\zeta = \zeta_L$) provided $n(\zeta_0) < n(\zeta_L)$. Hence, the individual phase peaks in the pulse $a(z,t) = |a|\exp(ikz - i\omega t)$ may move relative to one another (i.e., closer together for the present example). In such a way both the frequency and the wavenumber of the radiation pulse will change, as is given by Eqs. (4) and (5).

It should be pointed out that due to the local nature of the frequency shift (the dependence of $\Delta\omega$ on ζ), a laser pulse with a finite pulse length L will develop a spread

in frequency shifts. That is, the frequency shift at the front of the pulse may be different than the frequency shift at the back of the pulse. For example, consider a plasma wave with $v_p = v_g$ of the form $\delta k_p^2 = k_{p0}^2(\delta n_0/n_0)\sin k_{p0}\zeta$ and a laser pulse centered about $\bar{\zeta} = \pi$ with $L < \lambda_{p0}/2$ (see Fig. 1). The difference in the frequency shift at the center of the pulse with a point $\Delta\zeta$ away is given by $|(\Delta\omega(\bar{\zeta}) - \Delta\omega(\bar{\zeta} + \Delta\zeta))/\Delta\omega(\bar{\zeta})| = 1 - \cos\Delta\zeta$. This spread in frequency shifts may be quite significant.

Equations (4) and (5) provide convenient analytic expressions for the frequency and wavenumber shifts resulting from variations in the plasma parameter k_p^2. However, these expressions are only valid for a slowly varying envelope $b(\zeta,\tau)$, which implies that the frequency shifts must be small, $|\Delta\omega/\omega_0|^2 << 1$. To calculate the behavior of the vector potential for large shifts, $|\Delta\omega/\omega_0| \geq 1$, it is necessary to retain the $\partial^2/(\partial\zeta\partial\tau)$ derivative in the wave equation for $b(\zeta,\tau)$. Keeping this derivative, the wave equation can formally be solved for the case $\delta k_p^2(\zeta,\tau) = \delta k_p^2(\zeta)$, giving

$$b(\zeta,\tau) = \int_0^{\zeta} d\zeta' F(\zeta') \exp\left[i\omega_0(\zeta' - \zeta)/v_g\right] J_0\left[\alpha(\zeta',\zeta,\tau)\right], \tag{9}$$

$$\alpha(\zeta',\zeta,\tau) = \left(2c^2\tau \int_{\zeta}^{\zeta'} d\zeta'' \delta k_p^2(\zeta'')/v_g\right)^{1/2},$$

where J_0 is the Bessel function of order zero and $F(\zeta) = (\partial/\partial\zeta + i\omega_0/v_g)b_0(\zeta)$. In solving for $b(\zeta,\tau)$, it has been assumed $b(\zeta = 0) = 0$, i.e., $\zeta = 0$ is chosen to be in front of the pulse. Analysis of the above equation indicates that now both the amplitude $|b(\zeta,\tau)|$ and the phase evolve as a function of τ. Determination of the precise behavior of $b(\zeta,\tau)$ requires further computation.

In the analysis of Ref. 5, heuristic arguments based on Lorentz transformations of the dispersion relation are used to determine an expression for $\partial\omega/\partial z$. The above analytic theory may be used to derive an equation for $\partial\omega/\partial z$ by operating on Eq. (4) with $\partial/\partial z = \partial/\partial\zeta$. For the case of a plasma wave with phase velocity v_p, Eq. (4) gives

$$\frac{\partial\omega}{\partial z} = \frac{c^2}{2\omega_0\Delta v}\left[v_p\frac{\partial}{\partial z}\delta k_p^2(z - v_pt) - v_g\frac{\partial}{\partial z}\delta k_p^2(z - v_gt)\right], \tag{10}$$

which for $v_p = v_g$ reduces to the expression given in Ref. 5 when $\delta k_p^2 = k_{p0}^2\delta n/n_0$. Hence, the expression given in Ref. 5 has been shown to be valid provided i) $v_p = v_g$, ii) v_p is independent of z and t, iii) relativistic effects associated with $\gamma(z,t)$ are neglected and iv) the frequency shift remains small, $|\Delta\omega/\omega_0|^2 << 1$. Whether or not the arguments of Ref. 5 are valid for large shifts $|\Delta\omega/\omega_0| \geq 1$ remains uncertain.

The analytic theory presented above describes how a laser pulse becomes modified due to variations in the background plasma. Specifically, arbitrary variations in the plasma parameter $k_p^2(\zeta,\tau)$ leads to shifts in both the frequency and wavenumbers indicated by Eqs. (4) and (5). Provided these shifts are sufficiently small, the amplitude of the vector potential remains unchanged and propagates forward at the group velocity v_g. The above theory indicates that changes in the plasma density as a function of time lead to shifts in the radiation frequency. In particular, the possibility of upshifting the frequency of the laser pulse using a plasma wave has been examined and it is found that maximum frequency shifts result when $v_p = v_g$. For this case, $\Delta\omega$ increases linearly with the propagation distance $v_g\tau$ and positive frequency shifts require phasing the laser pulse such that it is centered at a position of decreasing density or, more precisely, at a position where $d\delta k_p^2/d\zeta < 0$. The above theory is valid, in general, for small frequency shifts, $|\Delta\omega/\omega_0|^2 << 1$. However, Eq. (8) implies that large shifts of order $|\Delta\omega| \sim \omega_0$ require propagation distances of order $c\tau \sim |\delta n_0/n_0|^{-1}\omega_0^2/\omega_{p0}^2$. Since, typically (for a KrF laser), $\omega_0^2/\omega_{p0}^2 >> 1$, this propagation distance can be quite large. The detailed examination of large shifts $|\Delta\omega| \sim \omega_0$ requires further evaluation of Eq. (9).

This work was supported by the Department of Energy and the Office of Naval Research.

References

1) K.G. Budden, *The Propagation of Radio Waves*, Cambridge University Press, Cambridge, 1985.

2) T. Tajima and J.M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).

3) P. Sprangle, E. Esarey, A. Ting and G. Joyce, Appl. Phys. Lett. **53**, 2146 (1988); E. Esarey, A. Ting, P. Sprangle and G. Joyce, Comments Plasma Phys. Controlled Fusion **12**, 191 (1989).

4) S.C. Wilks, J.M. Dawson and W.B. Mori, Phys. Rev. Lett. **61**, 337 (1988).

5) S.C. Wilks, J.M. Dawson, W.B. Mori, T. Katsouleas and M.E. Jones, Phys. Rev. Lett. **62**, 2600 (1989).

6) P. Chen, J.M. Dawson, R.W. Huff and T. Katsouleas, Phys. Rev. Lett. **54**, 693 (1985).

7) J.B. Rosenzweig, Phys. Rev. Lett. **58**, 555 (1987).

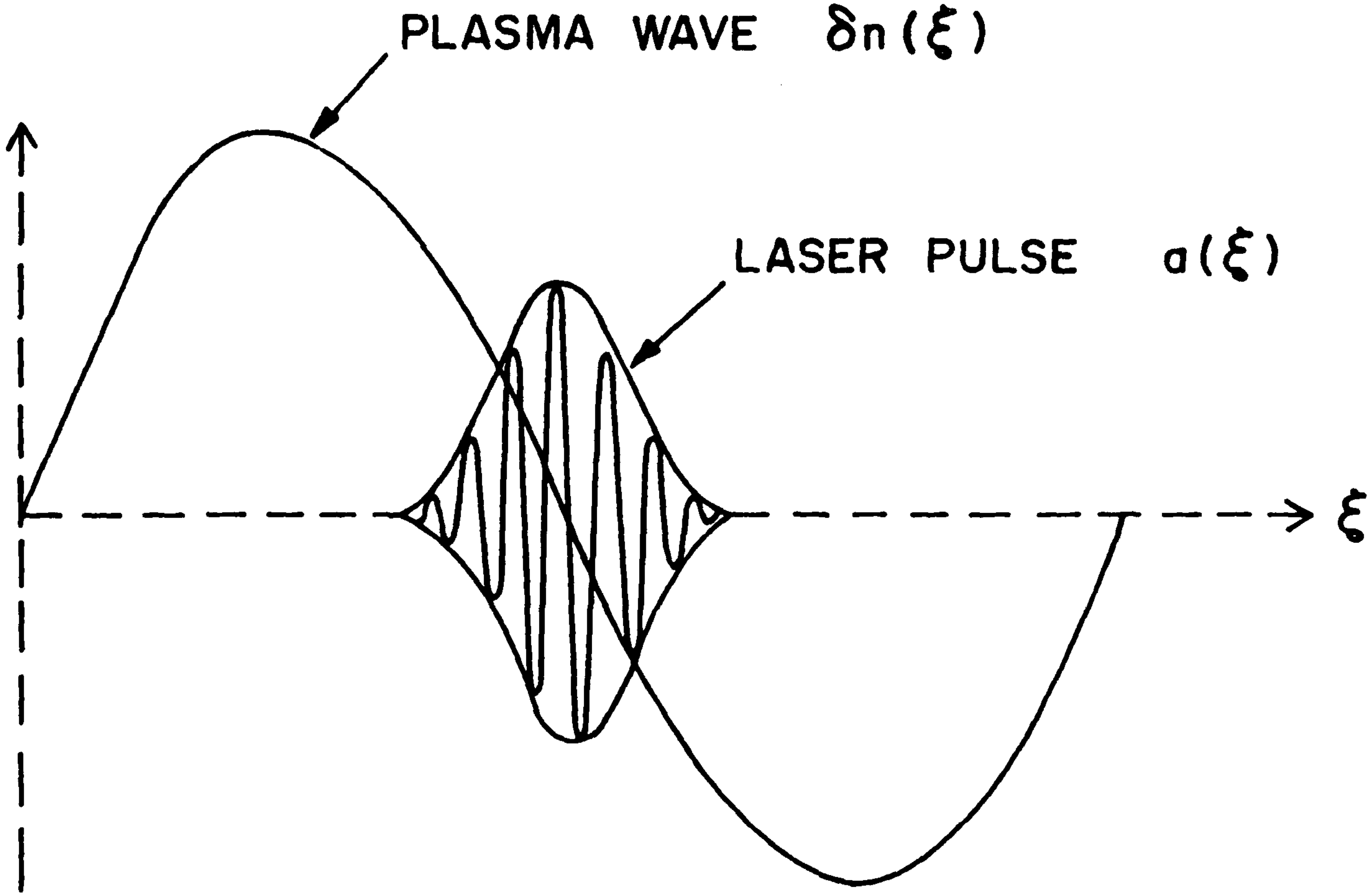

FIG. 1. Schematic of the upshifting of a laser pulse by a plasma wave with $v_p = v_g$. Positive frequency shifts require the laser pulse to be centered about regions of the wave with a decreasing density slope.

DISTRIBUTION LIST*

Naval Research Laboratory
4555 Overlook Avenue, S.W.
Washington, DC 20375-5000

Attn: Code 1000 - CAPT J. J. Donegan, Jr.
1001 - Dr. T. Coffey
1005 - Head, Office of Management & Admin.
1005.1-Deputy Head, Office of Management & Admin.
1005.6-Head, Directives Staff
0124 - ONR
2000 - Director of Technical Services
2604 - NRL Historian
3000 - Director of Business Operations
4603 - Dr. W. W. Zachary
4700 - Dr. S. Ossakow (26 copies)
4795 - Dr. C. A. Kapetanakos
4730 - Dr. R. Elton
4707 - Dr. W. M. Manheimer
4793 - Dr. S. Gold
4790 - Dr. P. Sprangle (20 copies)
4790 - Dr. C. M. Tang
4790 - Dr. M. Lampe
4790 - Dr. Y. Y. Lau
4790 - Dr. E. Esarey (20 copies)
4790 - Dr. J. Krall
4790 - Dr. A. Ting (20 copies)
4790A- B. Pitcher
6652 - Dr. N. Seeman
6840 - Dr. S. Y. Ahn
6840 - Dr. A. Ganguly
6840 - Dr. R. K. Parker
6850 - Dr. L. R. Whicker
6875 - Dr. R. Wagner
2628 - Documents (22 copies)
2634 - D. Wilbanks
1220 - 1 copy

* Every name listed on distribution gets one copy except for those where extra copies are noted

Dr. R. E. Aamodt
Lodestar Research Corp.
2400 Central Ave., P-5
Boulder, CO 80306-4545

Prof. I. Alexeff
University of Tennessee
Dept. of Electrical Engr.
Knoxville, TN 37916

Dr. D. Bach
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. W. A. Barletta
Lawrence Livermore National Lab.
P. O. Box 808
Livermore, CA 94550

Dr. D. C. Barnes
Science Applications Intl. Corp.
Austin, TX 78746

Dr. L. R. Barnett
3053 Merrill Eng. Bldg.
University of Utah
Salt Lake City, UT 84112

Dr. S. H. Batha
Lab. for Laser Energetics &
Dept. of Mech. Eng.
Univ. of Rochester
Rochester, NY 14627

Dr. F. Bauer
Courant Inst. of Math. Sciences
New York University
New York, NY 10012

Dr. Peter Baum
General Research Corp.
P. O. Box 6770
Santa Barbara, CA 93160

Prof. George Bekefi
Rm. 36-213
M.I.T.
Cambridge, MA 02139

Dr. Russ Berger
FL-10
University of Washington
Seattle, WA 98185

Dr. O. Betancourt
Courant Inst. of Math. Sciences
New York University
New York, NY 10012

Dr. B. Bezzerides
MS-E531
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Leroy N. Blumberg
U.S. Dept. of Energy
Division of High Energy Physics
ER-224/Germantown
Wash., DC 20545

Dr. Howard E. Brandt
Department of the Army
Harry Diamond Laboratory
2800 Powder Mill Road
Adelphi, MD 20783

Dr. Bob Brooks
FL-10
University of Washington
Seattle, WA 98195

Prof. William Case
Dept. of Physics
Grinnell College
Grinnell, Iowa 50221

Mr. Charles Cason
Commander, U. S. Army
Strategic Defense Command
Attn: CSSD-H-D
P. O. Box 1500
Huntsville, AL 34807-3801

Dr. Paul J. Channell
AT-6, MS-H818
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. A. W. Chao
Stanford Linear Accelerator Center
Stanford University
Stanford, CA 94305

Dr. Francis F. Chen
UCLA, 7731 Boelter Hall
Electrical Engineering Dept.
Los Angeles, CA 90024

Dr. K. Wendell Chen
Center for Accel. Tech.
University of Texas
P.O. Box 19363
Arlington, TX 76019

Dr. Pisin Chen
SLAC, Bin 26
P.O. Box 4349
Stanford, CA 94305

Dr. Marvin Chodorow
Stanford University
Dept. of Applied Physics
Stanford, CA 94305

Major Bart Clare
USASDC
P. O. Box 15280
Arlington, VA 22215-0500

Dr. Christopher Clayton
UCLA, 1538 Boelter Hall
Electrical Engineering Dept.
Los Angeles, CA 90024

Dr. Bruce I. Cohen
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. B. Cohn
L-630
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. Francis T. Cole
Fermi National Accelerator Laboratory
Physics Section
P. O. Box 500
Batavia, IL 60510

Dr. Richard Cooper
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Ernest D. Courant
Brookhaven National Laboratory
Upton, NY 11973

Dr. Paul L. Csonka
Institute of Theoretical Sciences
and Department of Physics
University of Oregon
Eugene, Oregon 97403

Dr. Chris Darrow
UCLA
1-130 Knudsen Hall
Los Angeles, CA 90024

Dr. J. M. Dawson
Department of Physics
University of California, Los Angeles
Los Angeles, CA 90024

Dr. Adam Drobot
Science Applications Intl. Corp.
1710 Goodridge Dr.
Mail Stop G-8-1
McLean, VA 22102

Dr. D. F. DuBois, T-DOT
Los Alamos National Laboratory
Los Alamos, NM 87545

Dr. J. J. Ewing
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. Frank S. Felber
11011 Torreyana Road
San Diego, CA 92121

Dr. Richard C. Fernow
Brookhaven National Laboratory
Upton, NY 11973

Dr. H. Figueroa
1-130 Knudsen Hall
U. C. L. A.
Los Angeles, CA 90024

Dr. Jorge Fontana
Elec. and Computer Eng. Dept.
Univ. of Calif. at Santa Barbara
Santa Barbara, CA 93106

Dr. David Forslund
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. P. Garabedian
Courant Inst. of Math. Sciences
New York University
New York, NY 10012

Dr. Walter Gekelman
UCLA - Dept. of Physics
1-130 Knudsen Hall
Los Angeles, CA 90024

Dr. Dennis Gill
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. B. B. Godfrey,
Chief Scientist
WL/CA
Kirtland AFB, NM 87117-6008

Dr. P. Goldston
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Prof. Louis Hand
Dept. of Physics
Cornell University
Ithaca, NY 14853

Dr. J. Hays
TRW
One Space Park
Redondo Beach, CA 90278

Dr. Wendell Horton
University of Texas
Physics Dept., RLM 11.320
Austin, TX 78712

Dr. H. Huey
Varian Associates
B-118
611 Hansen Way
Palo Alto, CA 95014

Prof. Stanley Humphries
Univ. of New Mexico
University Hill
Albuquerque, NM 87131

Dr. Robert A. Jameson
Los Alamos National Laboratory
AT-Division, MS H811
P.O. Box 1663
Los Alamos, NM 87545

Dr. G. L. Johnston
NW16-232
M. I. T.
Cambridge, MA 02139

Dr. Shayne Johnston
Physics Department
Jackson State University
Jackson, MS 39217

Dr. Mike Jones
MS B259
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. C. Joshi
7620 Boelter Hall
Electrical Engineering Department
University of California, Los Angeles
Los Angeles, CA 90024

Dr. E. L. Kane
Science Applications Intl. Corp.
McLean, VA 22102

Dr. Tom Katsouleas
UCLA, 1-130 Knudsen Hall
Department of Physics
Los Angeles, CA 90024

Dr. Rhon Keinigs MS-259
Los Alamos National Labortory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Kwang-Je Kim
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

Dr. S. H. Kim
Center for Accelerator Technology
University of Texas
P.O. Box 19363
Arlington, TX 76019

Dr. Joe Kindel
Los Alamos National Laboratory
P. O. Box 1663, MS E531
Los Alamos, NM 87545

Dr. Ed Knapp
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Peter Kneisel
Cornell University
F. R. Newman Lab. of Nucl. Studies
Ithaca, NY 14853

Dr. Norman M. Kroll
University of California, San Diego
San Diego, CA 92093

Dr. Michael Lavan
U. S. Army Strategic Defense Command
Attn: CSSD-H-D
P. O. Box 1500
Huntsville, AL 35807-3801

Dr. Kenneth Lee
Los Alamos National Laboratory
P.O. Box 1663, MS E531
Los Alamos, NM 87545

Dr. Baruch Levush
Dept. of Physics & Astronomy
University of Maryland
College Park, MD 20742

Dr. Chuan S. Liu
Dept. of Physics & Astronomy
University of Maryland
College Park, MD 20742

Dr. N. C. Luhmann, Jr.
7702 Boelter Hall
U. C. L. A.
Los Angeles, CA 90024

Dr. F. Mako
FM Technologies Corp.
205 South Whiting St.
Alexandria, VA 22304

Dr. Joseph Mangano
Science Research Laboratory
1600 Wilson Blvd.
Suite 1200
Arlington, VA 22209

Dr. Siva A. Mani
Science Applications Intl. Corp.
1040 Waltham Street
Lexington, MA 02173-8027

Dr. T. C. Marshall
Applied Physics Department
Columbia University
New York, NY 10027

Dr. Clare Max
Institute of Geophysics
& Planetary Physics
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. B. D. McDaniel
Cornell University
Ithaca, NY 14853

Col. Thomas Meyer
SDIO/DEO
The Pentagon, Rm. 1E180
Washington, DC 20301-7100

Prof. Kim Molvig
Plasma Fusion Center
Room NW16-240
M.I.T.
Cambridge, MA 02139

Dr. A. Mondelli
Science Applications Intl. Corp.
1710 Goodridge Drive
McLean, VA 22101

Dr. Mel Month
Brookhaven National Laboratories
Associated Universities, Inc.
Upton, L.I., NY 11973

Dr. Warren Mori
1-130 Knudsen Hall
U. C. L. A.
Los Angeles, CA 90024

Dr. P. L. Morton
Stanford Linear Accelerator Center
P. O. Box 4349
Stanford, CA 94305

Dr. Michael Mostrom
Mission Research Corp.
1720 Randolph Rd., S. E.
Albuquerque, NM 87106

Dr. John A. Nation
Laboratory of Plasma Studies
369 Upson Hall
Cornell University
Ithaca, NY 14853

Dr. Kelvin Neil
Lawrence Livermore National Lab.
Code L-321, P.O. Box 808
Livermore, CA 94550

Dr. K. C. Ng
Courant Inst. of Math. Sciences
New York University
New York, NY 10012

Dr. Robert J. Noble
S.L.A.C., Bin 26
Stanford University
P.O. Box 4349
Stanford, CA 94305

Dr. J. Norem
Argonne National Laboratory
Argonne, IL 60439

Dr. Craig L. Olson
Sandia National Laboratories
Plasma Theory Division 1241
P.O. Box 5800
Albuquerque, NM 87185

Dr. H. Oona
MS-E554
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Robert B. Palmer
Brookhaven National Laboratory
Upton, NY 11973

Dr. Richard Pantell
Stanford University
308 McCullough Bldg.
Stanford, CA 94305

Dr. John Pasour
Mission Research Corporation
8560 Cinderbed Rd.
Suite 700
Newington, VA 22122

Dr. Claudio Pellegrini
National Synchrotron Light Source
Brookhaven National Laboratory
Upton, NY 11973

Dr. Samual Penner
Center for Radiation Research
National Bureau of Standards
Gaithersburg, MD 20899

Dr. Melvin A. Piestrup
Adelphi Technology
13800 Skyline Blvd. No. 2
Woodside, CA 94062

Dr. Z. Pietrzyk
FL-10
University of Washington
Seattle, WA 98185

Dr. Hersch Pilloff
Code 421
Office of Naval Research
Arlington, VA 22217

Major E. W. Pogue
SDIO
The Pentagon, T-DE Rm. 1E180
Washington, DC 20301-7100

Dr. Anand Prakash
Ballistic Research Laboratory
Aberdeen Proving Ground, MD 21005

Dr. Don Prosnitz
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. R. Ratowsky
Physics Department
University of California at Berkeley
Berkeley, CA 94720

Dr. M. Reiser
University of Maryland
Department of Physics
College Park, MD 20742

Dr. C. W. Roberson
Office of Naval Research
Code 112S
800 N. Quincy Street
Arlington, VA 22217

Dr. Stephen Rockwood
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Harvey A. Rose, T-DOT
Los Alamos National Laboratory
Los Alamos, NM 87545

Dr. Marshall N. Rosenbluth
Institute for Fusion Studies
The Univ. of Texas at Austin
Austin, TX 78712

Dr. James B. Rosenzweig
Dept. of Physics
University of Wisconsin
Madison, WI 53706

Dr. N. Rostoker
Department of Physics
University of California at Irvine
Irvine, CA 92717

Dr. R. D. Ruth
SLAC, Bin 26
P. O. Box 4349
Stanford, CA 94305

Dr. Jack Sandweiss
Gibbs Physics Laboratory
Yale University
260 Whitney Avenue
P. O. Box 6666
New Haven, CT 06511

Dr. Al Saxman
Los Alamos National Laboratory
P.O. Box 1663, MS E523
Los Alamos, NM 87545

Prof. John Scharer
Electrical & Computer Engineering Dept.
University of Wisconsin
Madison, WI 53706

Dr. George Schmidt
Stevens Institute of Technology
Department of Physics
Hoboken, NJ 07030

Dr. Marlan O. Scully
Dept. of Physics & Astronomy
Univ. of New Mexico
800 Yale Blvd. NE
Albuquerque, NM 87131

Dr. Frank Selph
U. S. Department of Energy
Division of High Energy Physics, ER-224
Washington, DC 20545

Prof. P. Serafim
Northeastern University
Boston, MA 02115

Dr. Andrew M. Sessler
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

Dr. Richard L. Sheffield
Los Alamos National Laboratory
P.O. Box 1663, MS H825
Los Alamos, NM 87545

Dr. John Siambis
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, CA 94304

Dr. Robert Siemann
Dept. of Physics
Cornell University
Ithaca, NY 14853

Dr. J. D. Simpson
Argonne National Laboratory
Argonne, IL 60439

Dr. Charles K. Sinclair
Stanford University
P. O. Box 4349
Stanford, CA 94305

Dr. Sidney Singer
MS-E530
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. R. Siusher
AT&T Bell Laboratories
Murray Hill, NJ 07974

Dr. Jack Slater
Mathematical Sciences, NW
2755 Northup Way
Bellevue, WA 98009

Dr. Todd Smith
Hansen Laboratory
Stanford University
Stanford, CA 94305

Mr. J. J. Su
UCLA
1-130 Knudsen Hall
Los Angeles, CA 90024

Prof. Ravi Sudan
Electrical Engineering Department
Cornell University
Ithaca, NY 14853

Dr. Don J. Sullivan
Mission Research Corporation
1720 Randolph Road, SE
Albuquerque, NM 87106

Dr. David F. Sutter
U. S. Department of Energy
Division of High Energy Physics, ER-224
Washington, DC 20545

Dr. T. Tajima
Department of Physics
and Institute for Fusion Studies
University of Texas
Austin, TX 78712

Dr. R. Temkin (2 copies)
Mass. Institute of Technology
Plasma Fusion Center
Cambridge, MA 02139

Dr. Lee Teng, Chairman
Fermilab
P.O. Box 500
Batavis, IL 60510

Dr. H. S. Uhm
Naval Surface Warfare Center
White Oak Laboratory
Silver Spring, MD 20903-5000

U. S. Naval Academy (2 copies)
Director of Research
Annapolis, MD 21402

Dr. William A. Wallenmeyer
U. S. Dept. of Energy
High Energy Physics Div., ER-22
Washington, DC 20545

Dr. John E. Walsh
Department of Physics
Dartmouth College
Hanover, NH 03755

Dr. Tom Wangler
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. S. Wilks
Physics Dept.
1-130 Knudsen Hall
UCLA
Los Angles, CA 90024

Dr. Perry B. Wilson
Stanford Linear Accelerator Center
Stanford University
P.O. Box 4349
Stanford, CA 94305

Dr. W. Woo
Applied Science Department
University of California at Davis
Davis, CA 95616

Dr. J. Workman
Berkeley Research Associates
P.O. Box 241
Berkeley, CA 94701

Dr. Jonathan Wurtele
M.I.T.
NW 16-234
Plasma Fusion Center
Cambridge, MA 02139

Dr. Yi-Ton Yan
SSC Central Design Group
c/o LBL 90-4040
University of California
1 Cyclotron Rd.
Berkeley, CA 94720

Dr. M. Yates
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Ken Yoshioka
Laboratory for Plasma and Fusion
University of Maryland
College Park, MD 20742

Dr. R. W. Ziolkowski, L-156
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Do NOT make labels
for these two-below:
Records---(1 copy)

Naval Research Laboratory
Washington, DC 20375-5000
Code 2630
Timothy Calderwood